Simultaneous fusion, imaging and encryption of multiple objects using a single-pixel detector

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Abstract

A novel technique for the simultaneous fusion, imaging and encryption of multiple objects using a single-pixel detector is proposed. Here, encoded multiplexing speckles are employed to illuminate multiple objects simultaneously. The mixed light reflected from the objects is detected by a single-pixel detector. An iterative reconstruction method is used to restore the fused image by summing the multiplexed speckles and detected intensities. Next, clear images of the objects are recovered by decoding the fused image. We experimentally obtain fused and multiple clear images by utilizing a single-pixel detector to collect the direct and indirect reflected light. Technically, by utilizing the speckles with per-pixel exposure control, multiple objects' information is multiplexed into the detected intensities and then demultiplexed computationally under the single-pixel imaging and compressed sensing schemes. An encryption experiment is performed by setting the multiplexed speckles' encoding as keys. We find that the encryption performance in a scattering medium is better than that in a clear medium.

INTRODUCTION

With the development of semiconductor technology, traditional imaging matrix detectors (such as charge-coupled devices [CCDs] and complementary metal-oxide-semiconductors [CMOSs]) tend to have large arrays of small pixels. The latest matrix detectors can capture high-resolution images with billions of pixels. Alternatively, an imaging system [1-7] based on an un-scanned single-pixel detector (such as a photodetector [PD] or photomultiplier tube [PMT]) has received increasing attention from researchers in recent years. This single-pixel imaging (SPI) system employs random speckles to illuminate the object, and then the intensities of the reflected or transmitted light from the object are acquired by an un-scanned single-pixel detector. Subsequently, the image of the object can be recovered based on the correlation between the illumination speckles and the detected intensities. This new imaging system, which includes an integrated computational algorithm, can reduce the cost or size of matrix detectors, especially in the infrared and terahertz region of the spectrum, where matrix detectors do not have such good specifications compared to their performance in the visual spectrum. Traditional SPI systems for image encryption [8-11] have been studied, where the random speckles or/and the detected intensities are utilized as keys. Here, an SPI technique comprising multi-object fusion, imaging and encryption is proposed, and an experimental study to validate this SPI technique is conducted. Encoded multiplexing speckles enable the simultaneous illumination of multiple objects and can be applied to fuse, image and encrypt these objects. The experimental results demonstrate the effectiveness of the proposed technique, even in a scattering environment.

This technique originated from compressed sensing (CS) theory [12] that allows the recording an image consisting of N^2 pixels using much fewer than N^2 measurements if it can be transformed to a basis where most pixels have negligibly small values. For example, theoretically, a 1-mega-pixel array could potentially be used to reconstruct a 4-mega-pixel image. Specifically, a random sample of the 4-mega-pixel image is taken and then recovered through sparse signal reconstruction methods. This is possible because natural images tend to be sparse (i.e., only a small fraction of these projections have relevant information) in some bases of functions. The hardware limitations of traditional imaging systems in terms of their spatial resolution and temporal resolution can be effectively addressed using this characteristic. To date, several matrix imaging systems [13-15] have been built, and the effectiveness of the theory has been confirmed experimentally. For example, a method of efficient space-time sampling with pixel-wise coded exposure to reconstruct a video from a single coded image while maintaining high spatial resolution has been proposed [13]. Additionally, Liang *et al*. have accomplished single-shot compressed ultrafast photography at one hundred billion frames per second with random sampling [14]. Collecting the spectral information of an imaging scene via random sampling has also been proposed [15].

Simultaneously, the CS algorithm has also received substantial attention for SPI. The first work on compressive SPI [3] was performed at Rice University; the results showed that compressive SPI can obtain a high-quality image with far fewer Nyquist measurements. Subsequently, the CS algorithm has become widely used in SPI systems. Nevertheless, in the above SPI-related references

[1-7], the imaging scene is completely sampled by the illumination speckles. However, according to the above analysis, accurate image information can be recovered when the scene is incompletely sampled by illumination speckles. Then, speckles with observed in spatial multiplexing mode can be used to simultaneously sample multiple objects in an orderly manner. In other words, an SPI system with spatial multiplexed speckles can be employed to achieve the fusion, imaging and encryption of multiple objects.

The whole procedure of the proposed technique is demonstrated in Fig. 1, in which four objects serve as an example. First, the computer program produces four complementary binary encoded matrices—B1, B2, B3, and B4—and multiplexed speckles (SS) S. The illumination speckles C are produced by resizing the matrices obtained by multiplying the multiplexed speckles and encoded matrices. The assembling procedure of illumination speckle C_j is shown in the gray frame of Fig. 1. The illumination speckles are loaded into the projection system and then projected onto the scene. The reflected light intensity G of the four objects is detected by a single-pixel detector. The fused image of the four objects can be restored using an iterative reconstruction method. Next, four random sampling images named f_{1p}, f_{2p}, f_{3p} and f_{4p}, indicating different random partial object information, can be recovered by multiplying the fused image and encoded matrices. Finally, the original images of the corresponding object can be obtained using the CS algorithm. Here, multiple images are fused and encrypted by integrating them in the mixed measurement. According to the above analysis, the encoded matrices are very important when recovering accurate image information during secondary processing. When the encoded matrices are unknown, accurate object information cannot be obtained. Accordingly, using the encoded matrices of the proposed method as keys can result in the encryption of the objects' information.

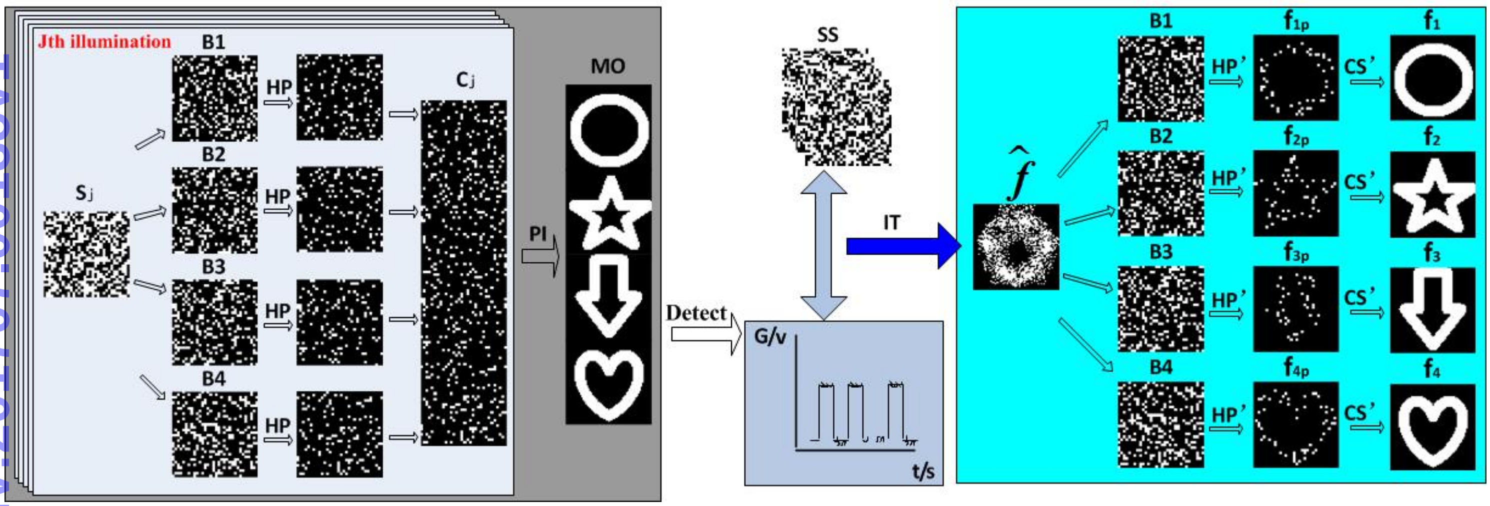

Fig. 1. Procedure of the proposed method: SS: multiplexed speckles, S_j: the j-th multiplexed speckle; B1-B4: four complementary binary encoded matrices; C_j: the j-th illumination speckle; HP: the Hadamard product of S_j and the encoded matrices; PI: projection illumination; MO: multiple objects; G: intensities detected by the single-pixel detector; IT: the fused information $\hat{f}$ calculated via an iterative reconstruction method; HP': Hadamard product of the fused information $\hat{f}$ and the encoded matrices; f_{1p}, f_{2p}, f_{3p} and f_{4p}: four random sampling images; CS': computed images of four objects based on the CS algorithm; f_1, f_2, f_3 and f_4: four recovered images.

Compared with the prior literature concerning SPI methods, in addition to the advantages of SPI, the proposed technique has the following additional advantages. First, the united process, which incorporates the encryption of the fused image with the compressed acquisition of multiple objects, ensures the security of private content and, thus improves the encryption performance of the SPI system relative to conventional single-pixel encryption methods (in which speckles or/and detected intensities are employed as keys) by providing a third key based on the encoded matrices used in this method. Second, multiple objects can be fused, imaged and encrypted using sub-Nyquist measurements, which significantly reduces the data acquisition and allows faster data communication to users. Therefore, the system efficiency can be greatly increased using the proposed method.

RESULT

Experimental setup: The experimental system used to study the proposed approach is described as follows. A 532-nm continuous wave (cw) laser serves as the light source. A digital micro-mirror device (DMD: TI DLP 6500 system) is used to generate illumination speckles. Three single-pixel detectors (Thorlabs PMT-PMM02) and data acquisition system (NI USB-6211) are employed for light detection and data acquisition, respectively. The laser beam enters a beam expander (BE) and then passes through the DMD, which provides time-varying illumination speckles. The direct and indirect reflected light from the multiple objects (MO) is collected by collecting lens and measured by the single-pixel detectors, and then the intensity data are sent to a computer through the data acquisition system. The DMD has a tilted micro-planar mirror array; each of the flat mirrors can be tilted ±12° independently to the "ON" or "OFF" state. When a micro-mirror is tilted +12°, the corresponding pixel of the speckle is sampled and is equal to 1; when it is tilted -12°, the corresponding pixel of the speckle is equal to 0. The DMD system with per-pixel exposure control can achieve the anticipant illumination speckles, which is the foundation of the successful implementation of the proposed technique.

Various patterns of the multiplexed speckles can be employed in the SPI system. Random patterns, in which each mask has a random distribution of binary values, have been widely used. In this case, complex operations are required to obtain the object information. Hadamard patterns provide another strategy that enables the reconstruction of the image with a linearly iterative algorithm, which requires very low computational complexity. Here, Hadamard patterns of the multiplexed speckles are chosen for our experiments.

A Hadamard pattern is based on orthogonal discrete square waves, with values of either +1 or −1. Because the illumination speckles produced by the DMD system are binary, positive and negative reflection values cannot be readily utilized. To address this issue, two approaches can be employed. The first approach involves the use of transformative Hadamard matrices and ensures that all entries consist of values of either 1 or 0. The second approach involves a pair of matrices that are related to the Hadamard matrix by a subtraction operation. The second approach can improve the signal-to-noise ratio (SNR) of the measurements and is utilized in our system [7]. The process is described as follows. The entries of a Hadamard matrix H are either +1 or −1. We create the complementary pair $H_{\pm}=(E\pm H)/2$, where E represents a matrix for which all entries are equal to 1. As a result, we have one matrix H_{+} where the original +1 entries retain their value, and the −1 entries become zero. In the other matrix H_{-}, unity-valued entries become zero, and the −1 entries become 1. As the detected intensity is linear with the speckles, the speckles with H_{+} and H_{-} patterns are employed in the projection; thus, the coefficient under the Hadamard basis can be calculated by subtracting the two detected intensities.

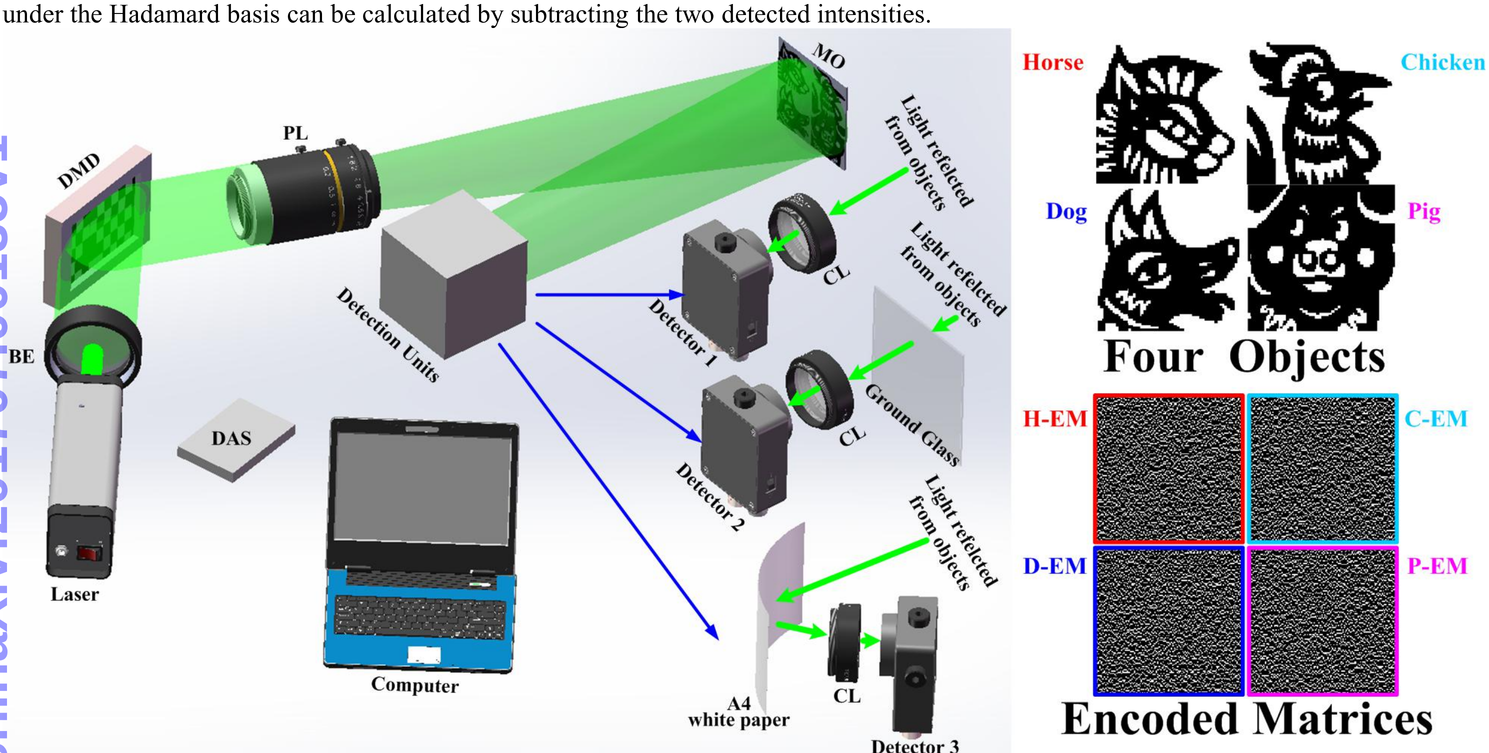

Fig. 2. The configuration of the SPI system for the simultaneous fusion, imaging and encryption of multiple objects. BE: beam expander; DMD: digital micro-mirror device; PL: projection lens; MO: multiple objects; CL: collecting lens; DAS: data acquisition system; Detectors 1, 2, and 3: single-pixel detectors. H-EM, C-EM, D-EM and P-EM labeled with different color borders are encoded matrices applied to four cartoon binary animals (horse, chicken, dog and pig), respectively.

Four binary cartoon animals (horse, chicken, dog and pig) printed on A4 paper are employed as the multiple objects in the experiment and are placed side by side at the object position, as shown in Fig. 2. The 3×3 mirrors of the DMD are combined into a speckle cell that corresponds to an image pixel, and the intermediate 768×768 mirrors are utilized in the experiment. Thus, the resolution of the entire lighted area is 256×256 pixels. The imaging area is divided into four areas; thus, the imaging resolution is 128×128 pixels. Four 128×128 pixel encoded matrices labeled with borders of different colors are shown in Fig. 2 and arranged in a 2×2 manner. These matrices were produced by a random process and have complementary orthogonal properties with a compression ratio of 25%. During the acquisition process, the encoded matrices remain unchanged. The pre-process is described as follows. First, 16384 pairs of complementary Hadamard speckles are generated as multiplexed speckles with values of 0 or 1 according to the above method. Next, four-combined illumination speckles with 768×768 mirrors are reproduced by arranging and resizing intermediate matrices via multiplying the Hadamard speckles with the encoded matrices and are then loaded into the DMD system. Finally, the four-combined illumination speckles are employed to illuminate the four objects, and the direct and indirect reflected lights from four objects is collected by the single-pixel detectors. Here, each subpart of the illumination speckles can illuminate the corresponding object without crossing. The direct reflected light from the four objects is collected by the collecting lens and detected by detector 1. The reflected light from the four objects passes through ground glass, and then, the indirect reflected light is detected by detector 2. The reflected light from the four objects is reflected

by a sheet of white A4 paper, and then, the indirect reflected light is detected by detector 3, which is a reverse-oriented photodiode without a direct view of the objects. The fusion, imaging and encryption of the multiple objects are achieved using the intensities detected by the three detectors, respectively.

Experimental results of multi-object fusion and imaging: An evolutionary linear iterative method [7] aiming to reconstruct the image in significantly less time than conventional CS is proposed. The evolutionary linear iteration scheme chooses a subset of the Hadamard speckles to recover the fused image of the multiple objects by selecting the patterns with the most significant intensities measured by the single-pixel detector. The recovered fusion images based on the intensities of the direct reflected light are shown in Fig. 3, and the columns present the results obtained using different numbers of Hadamard speckles. Based on the results, the SNRs of the recovered results increase as the number of multiplexed speckles increase. However, we cannot identify the multi-object information from the results in Fig. 3. Fortunately, based on the properties of encoded matrices, four compressed images can be obtained by multiplying the fused image with the encoded matrices, as shown in the first row of Fig. 4. Finally, the results of the final recovered images obtained using compression sensing are shown in the second row of Fig. 4. The experiment was determined to be successful based on the fact that completely accurate image information can be recovered exactly from compressed samples via the CS algorithm. The results show that the quality of recovered images is affected by the SNR of the fused image and that a positive correlation exists between them. The differences among the images reconstructed from the fused images with coverage spanning compression ratios from 25% to 100% are nearly negligible. According to the results, different encoded matrices can effectively achieve the fusion of multiple object images. The compression ratio of the encoded matrices is 25%, so the fusion of the information of the four images is achieved. If the compression ratio is further reduced, the images of more objects can be fused and imaged using the results of one measurement. However, in the traditional SPI system, each object must be individually measured once to maintain the same image resolution. Thus, the proposed method can effectively reduce the data acquisition and improve the imaging efficiency. Note that the images are not subjected to any additional processing, such as filtering.

Scattering media limit optical observations because their random refractive index variations distort the spherical wavefront generated by every point source, resulting in a smeared image at a matrix detector [16]. In our imaging system, a single-pixel detector is employed to measure the whole reflected intensity, and the intensity distribution is not of concern; thus, the proposed technique can be employed to fuse and image multiple objects through scattering media. We used two different detection units for image reconstruction in a scattering environment: 1) detector 2 covered with a piece of ground glass and 2) reversely placed detector 3 with a piece of white A4 paper as a reflecting diffuser. In the first case, the reflected light from the objects passes through the ground glass before being collected by the collecting lens and directed into detector 2. Fused image reconstructions with compression obtained in this situation are shown in Fig. 5. These images appear noisy because the light collected by detector 2 was relatively weak as a result of the low transmittance of the ground glass, resulting in a detection signal with a lower SNR. Based on the correlation coefficient with the reconstruction utilizing complete Hadamard basis for direct reflected light, the fused result improves as the number of multiplexed speckles increases, and the best result is similar to that obtained with a compression ratio of 25% in the above situation. We use the proposed method to restore the images of the four objects shown in Fig. 6. The results indicate that we can clearly identify the object information. In the second case, the reflected light from the objects is reflected by a sheet of white A4 paper and then collected by the collecting lens and directed into detector 3. The fused image reconstructions with compression obtained in this situation are shown in Fig. 7. The SNRs of the recovered images are lower than those in the first case because the light collected by the detector was weaker because of the low reflectivity of white A4 paper. Although scattering reduces the SNR, the four objects shown in Fig. 8 can still be perceived. The ability to image multiple objects through scattering media makes our system valuable in numerous applications, ranging from optical communication through turbulent atmosphere to microscopic imaging in turbid tissues.

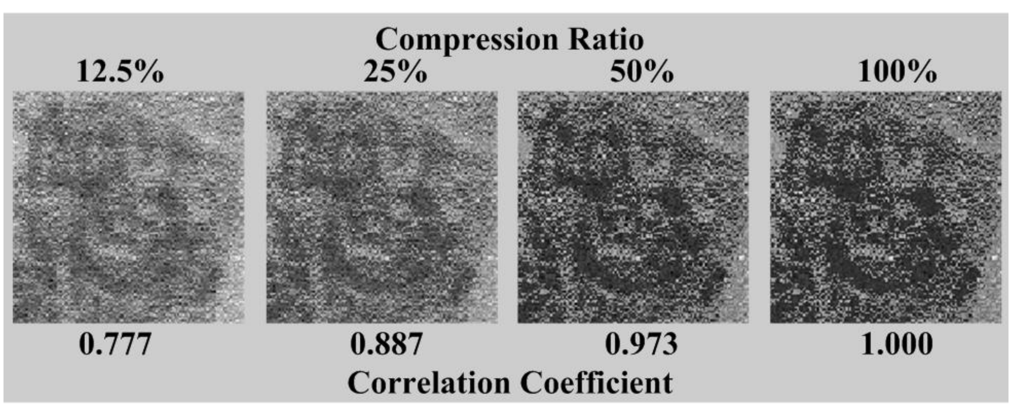

Fig. 3. Fused image reconstruction with compression using direct reflected light. Scene reconstructed with different compression ratios according to the correlation coefficient between the recovered images and the reconstruction utilizing a complete Hadamard basis (100% compression ratio).

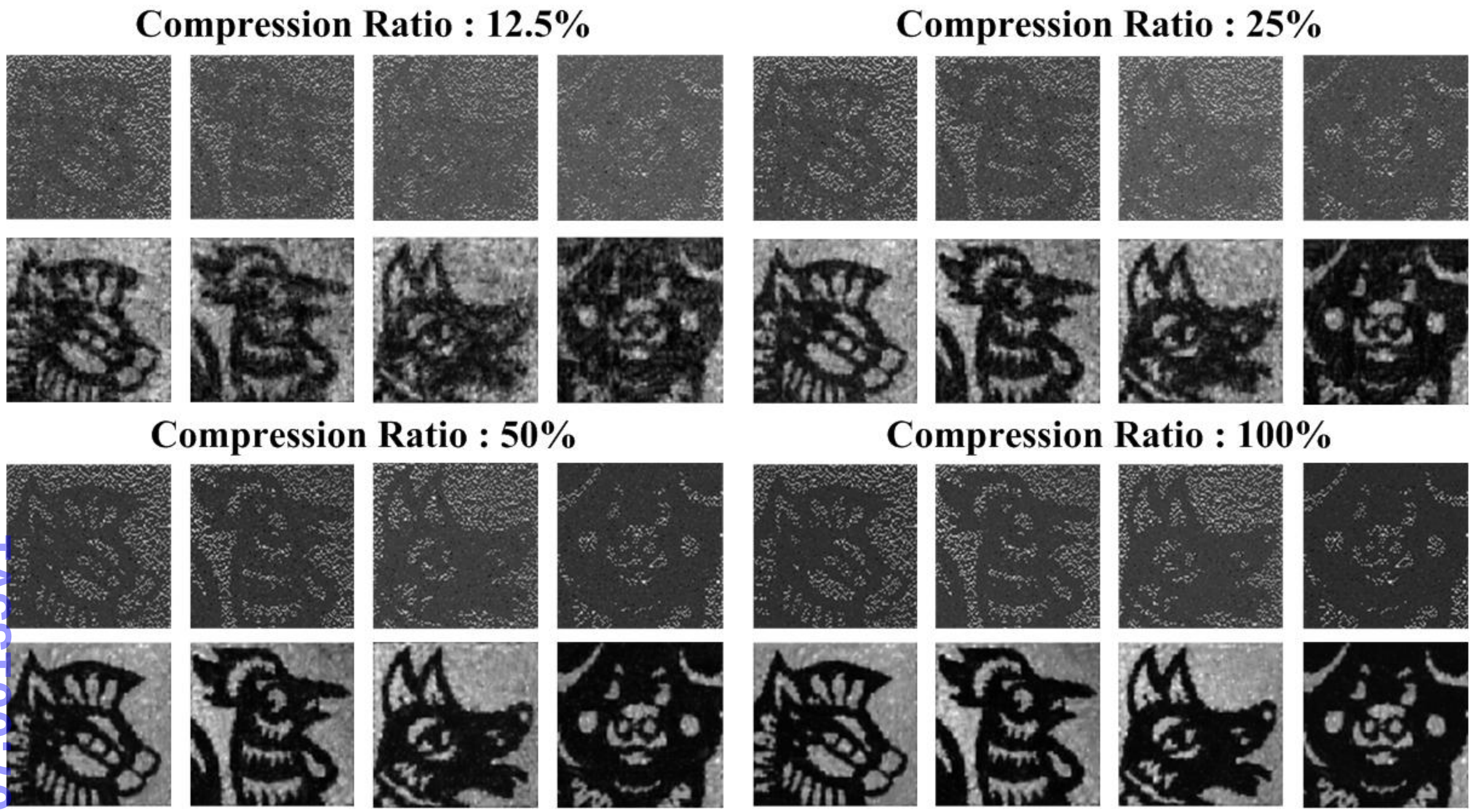

Fig. 4. Multiple objects reconstructed with different compression ratios using direct reflected light. The first row of each graph represents the compressed images obtained by multiplying the fusion result with the encoded matrices, and the second row presents the final recovered results.

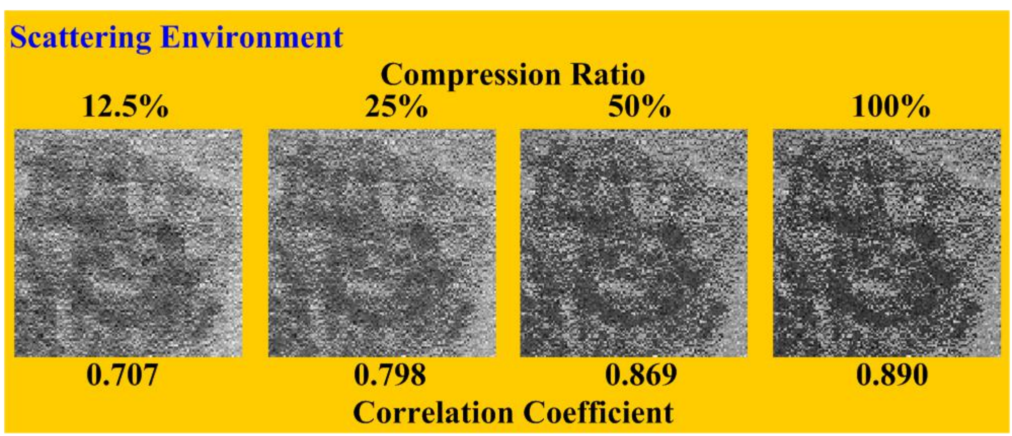

Fig. 5. Fused image reconstruction using detector 2 under different compression ratios in a scattering environment. Scene reconstructed under different compression ratios, indicating the correlation coefficient between recovered images and the reconstruction utilizing the complete Hadamard basis for direct reflected light (100% compression ratio).

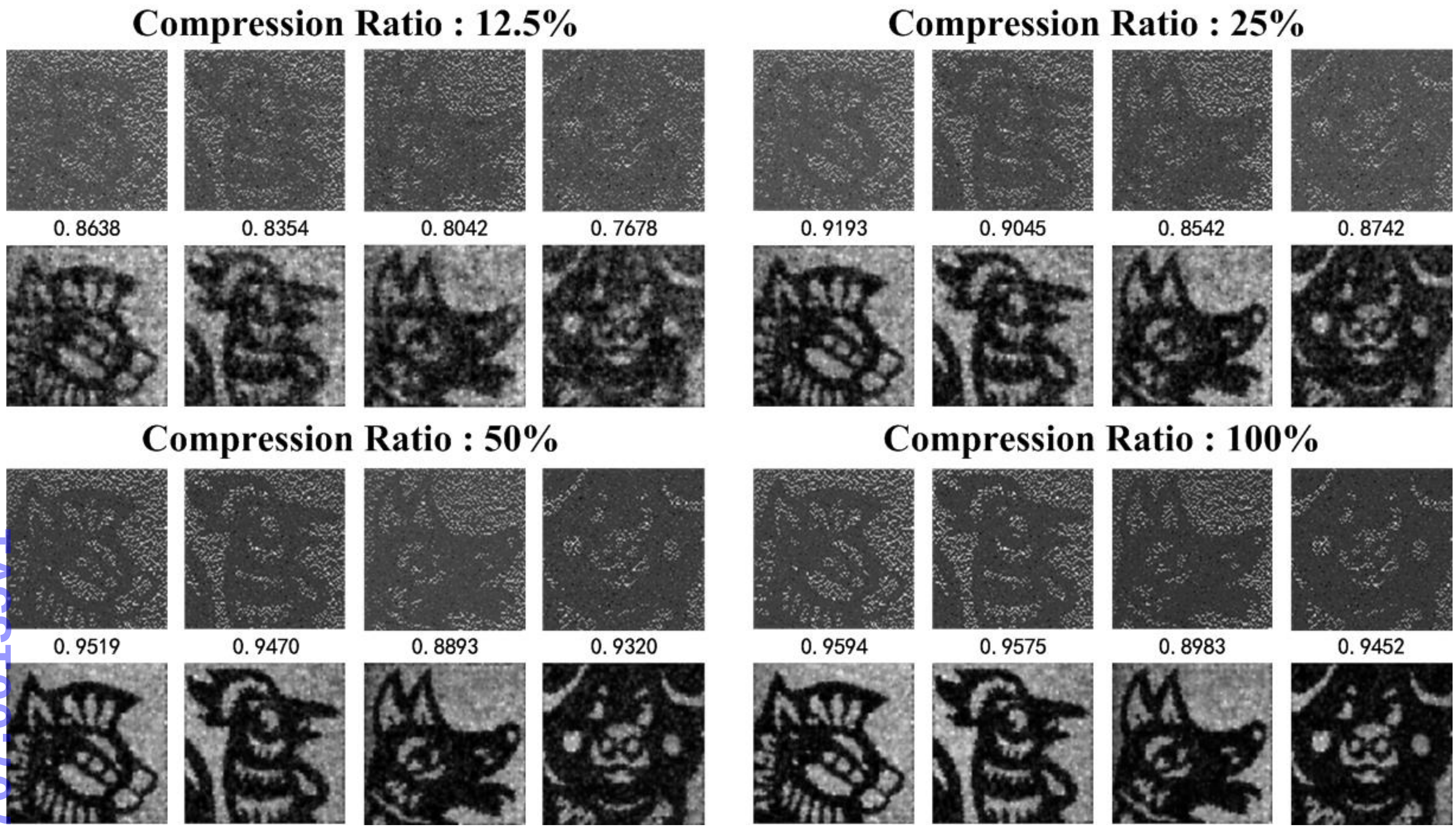

Fig. 6. Multiple objects reconstructed using detector 2 under different compression ratios in a scattering environment. The first row of each graph represents the images obtained by multiplying the fusion result with the encoded matrices, and the second row represents the final recovered results. The numbers indicate the correlation coefficients between the recovered images and the reconstruction utilizing the complete Hadamard basis for direct reflected light (100% compression ratio).

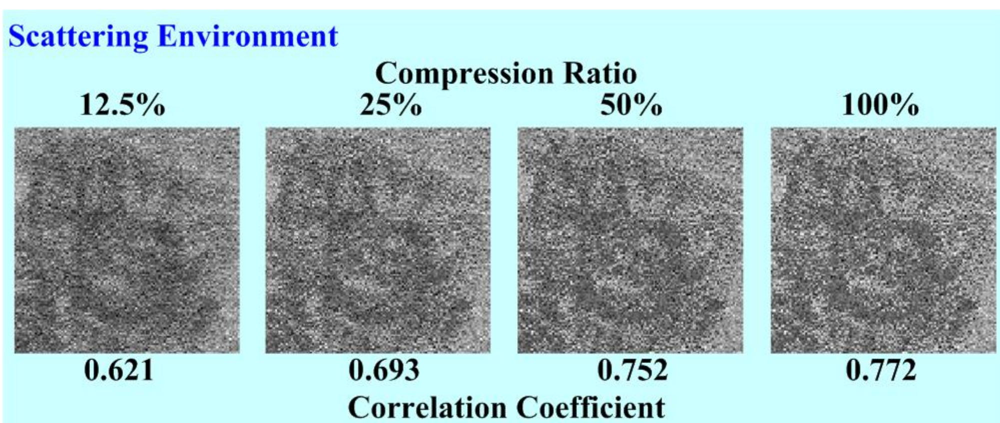

Fig. 7. Fused image reconstruction using detector 3 under different compression ratios in a scattering environment. Scene reconstructed under different compression ratios, indicating the correlation coefficient between recovered images and the reconstruction utilizing the complete Hadamard basis for direct reflected light (100% compression ratio).

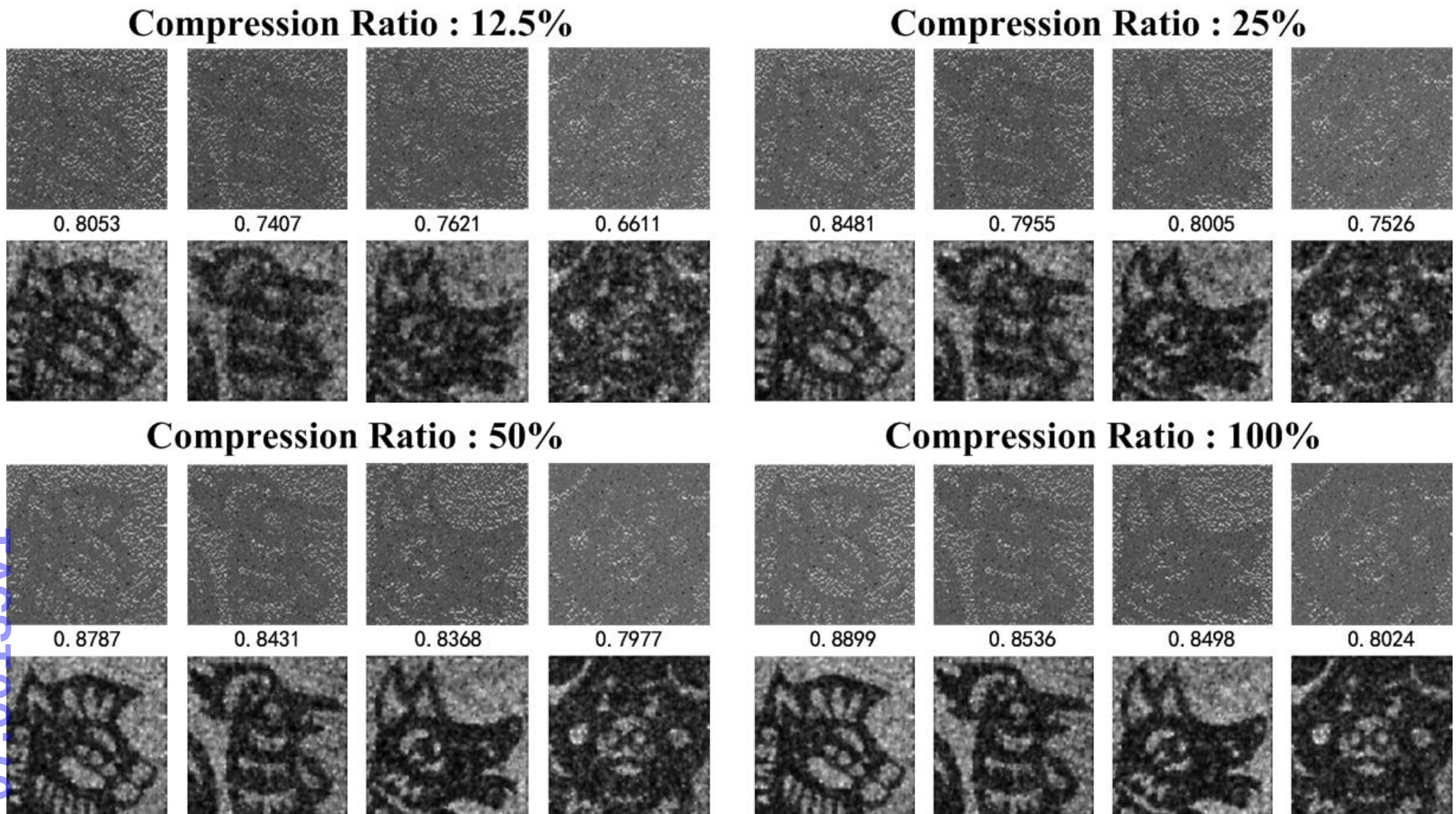

Fig. 8. Multiple objects reconstructed using detector 3 under different compression ratios in a scattering environment. The first row of each graph represents the images obtained by multiplying the fusion result with the encoded matrices, and the second row represents the final recovered results. The numbers indicate the correlation coefficients between recovered images and the reconstruction utilizing the complete Hadamard basis for direct reflected light (100% compression ratio).

Experimental encryption results: We use the experimental results to verify the system's encryption capability. In the information encryption transmission process, the detected intensities and multiplexed speckles are transmitted as public information, and only the four encoded matrices are transmitted in an encrypted manner. In other words, the encoded matrices are the only keys. It is assumed that, during the information transmission, the eavesdropper obtains multiplexed speckles and intensities detected by the single-pixel detector, determines the encoded matrices with a certain level of accuracy, and then uses the partial accurate information to restore the images of the four encrypted objects. Fig. 9 shows the restoration of multiple objects under different bit error ratios and different numbers of Hadamard basis using the direct reflected intensities. According to the results, as the bit error ratios decrease, the quality of the recovered images gradually improves. The quality of the recovered images also improves as the compression ratio increases. The correlation coefficients in the figure confirm these conclusions. Note that the restored image is simultaneously affected by the bit error ratio and the number of multiplexed speckles. To obtain high-quality object information, an eavesdropper not only requires high-precision encoded matrices but must also use more speckles to restore the image. The system's encryption performance can be further improved by the encrypted transmission of speckles or/and intensities.

Image encryption in a scattering environment was also performed. Fig. 10 shows the restoration of multiple objects at different bit error ratios and different numbers of Hadamard basis using the indirect reflected intensities from detector 2. The results show that the relationship between the restored image quality and the error ratio is the same as that determined for the above situation. However, for the second scattering environment, because of the lower SNR of the fused image, the quality of recovered images shown in Fig. 11 deteriorates rapidly relative to the previous situation. These findings are confirmed by the correlation coefficients shown in the figure. Note that when the compression ratio exceeds a certain value, the qualities of the recovered images are not necessarily enhanced as the compression ratio increases. According to the results, the accurate encryption information sought by the eavesdropper becomes more difficult to obtain in a scattering environment than in a clear medium. Thus, a scattering medium improves the encryption performance.

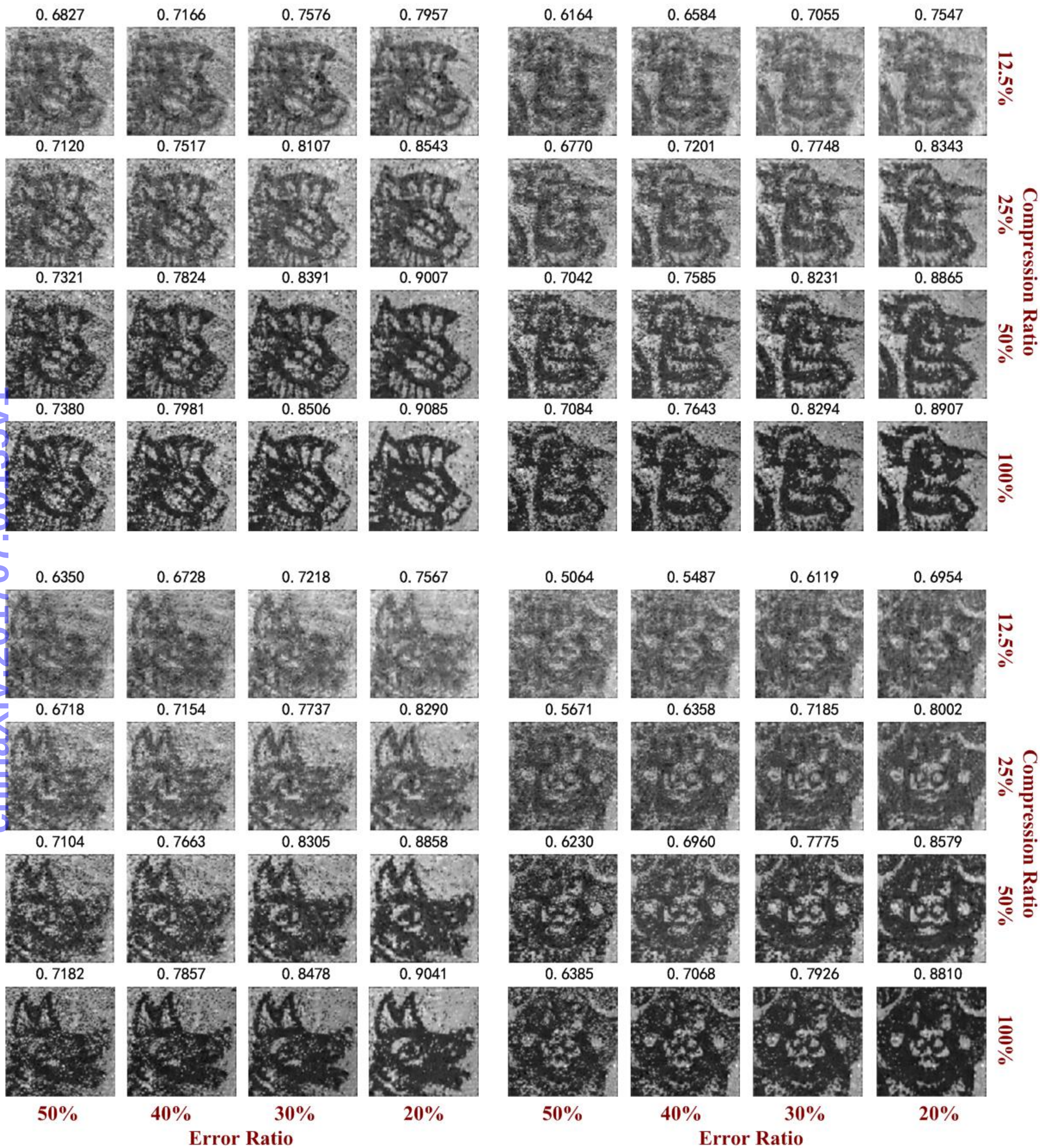

Fig. 9. Image encryption experiment using the direct reflected intensities from detector 1. The results obtained under error ratios of 50%, 40%, 30% and 20% for the encoded matrices are shown. The numbers indicate the correlation coefficients between the recovered images and the reconstruction utilizing the complete Hadamard basis for direct reflected light (100% compression ratio).

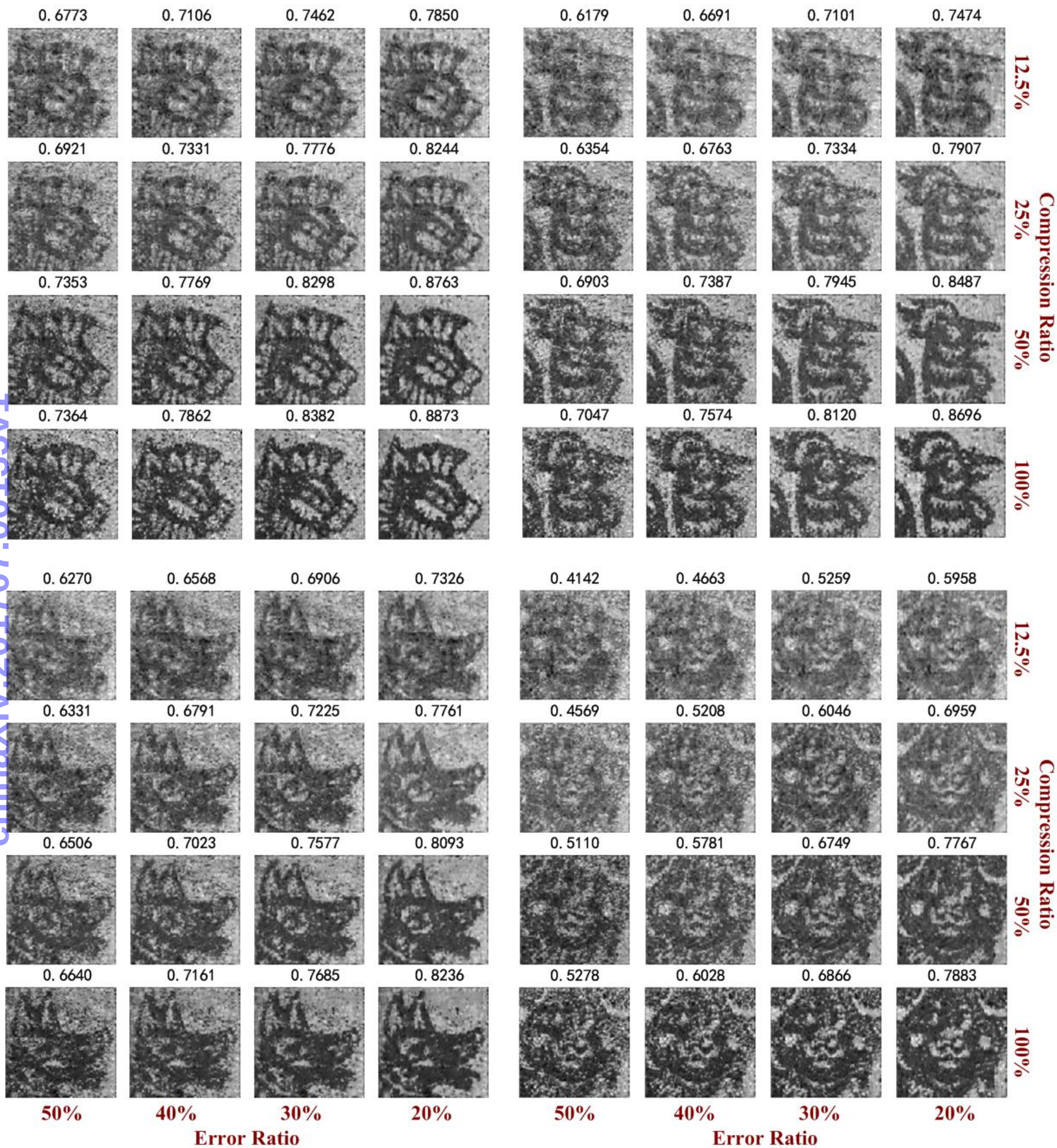

Fig. 10. Image encryption experiment using the scattered reflected intensities from detector 2. The results under error ratios of 50%, 40%, 30% and 20% for the encoded matrices are shown. The numbers indicate the correlation coefficients between the recovered images and the reconstruction utilizing the complete Hadamard basis for direct reflected light (100% compression ratio).

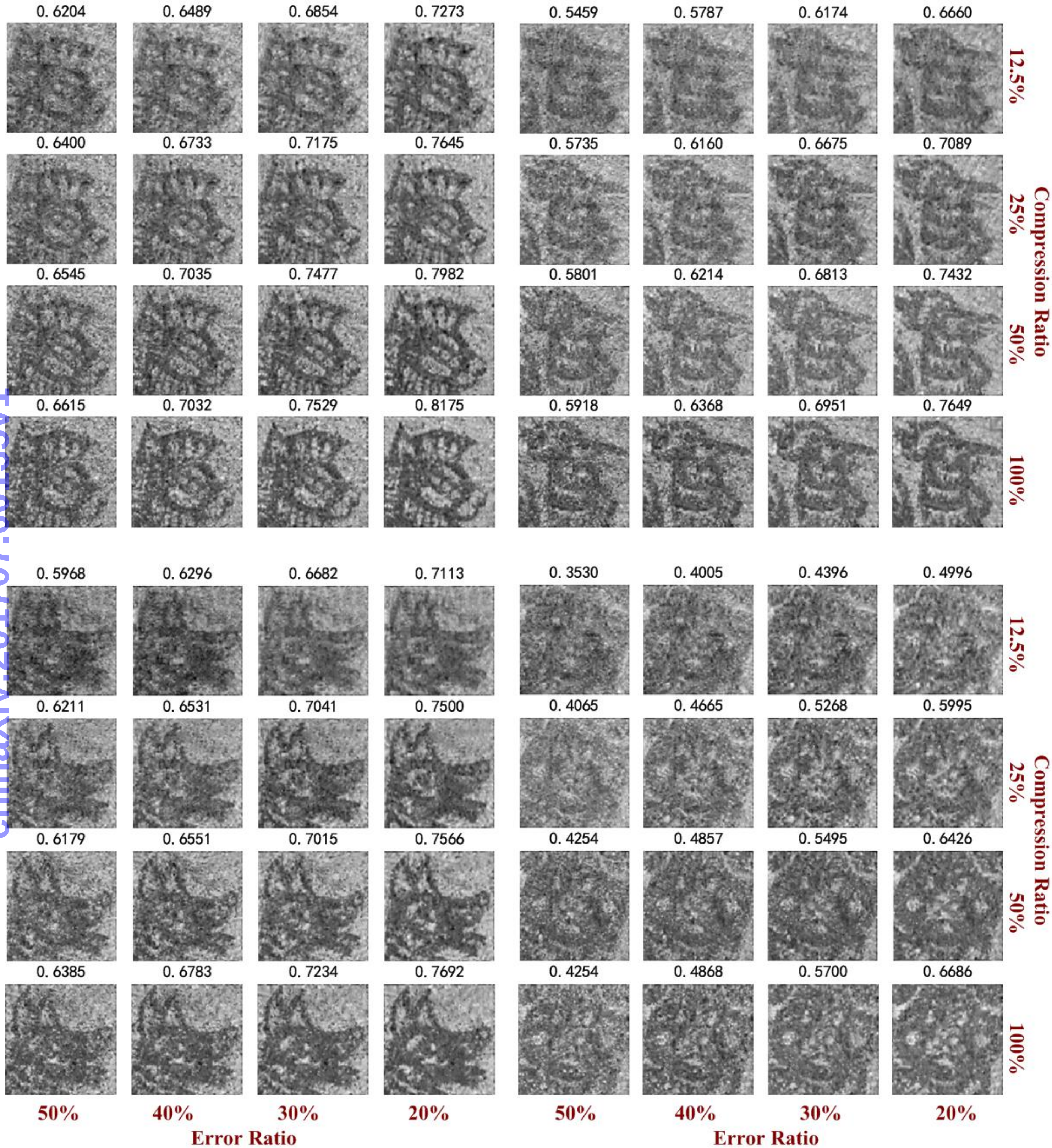

Fig. 11. Image encryption experiment using the scattered reflected intensities from detector 3. The results under error ratios of 50%, 40%, 30% and 20% for the encoded matrices are shown. The numbers indicate the correlation coefficients between the recovered images and the reconstruction utilizing the complete Hadamard basis for direct reflected light (100% compression ratio).

DISCUSSION

Based on CS theory, the vast majority of objects in some transformations have sparse features; as a result, random samples of images can be employed to obtain complete and accurate image information. This characteristic has been applied in many systems. By applying this principle to an SPI system, a method for compressing multiple objects by using multiplexed speckles is proposed. Based on the multiplexed speckles, an SPI technique for multi-object fusion, imaging and encryption is developed and tested experimentally. The results revealed that the proposed method enables the simultaneous imaging of multiple objects, even in a scattering environment, and is highly efficient for information encryption. Note that in this paper, the fused image contains four objects' information; thus, the compression ratio is a quarter of the above value relative to the whole information. In other words, the proposed method realizes the fusion, imaging and encryption of multiple objects via sub-Nyquist measurements.

Additionally, the fusion, imaging and encryption of more objects can be achieved by further compressing the encoded matrices. In general, the central challenge addressed by this method is to find an architecture that effectively balances the final recovery image quality with the number and pattern of the encoded matrices. The choice of the encoded matrix plays a key role in image reconstruction. Because various matrices can be chosen, the problem of optimizing the encoded matrix should be carefully studied in the future. However, when we use this method to encrypt multiple objects, the optimal encoded matrix with high encryption performance and transmission efficiency can be pre-selected by investigating the sparse characteristics of the transmitted information. In addition, due to environmental interference, light source instability and other factors, the quality of the information acquired by the SPI system is not high; thus, efficient system configuration and restoration algorithms must be explored. We believe that this new technique will pave the way for the use of this SPI system in several fields, including optical communication, imaging around corners, and especially imaging multiple objects in a scattering medium, such as water or fog.

METOD

The reconstruction of the proposed technique involves two main steps: spatial multiplexing and multi-image demultiplexing.

Spatial Multiplexing

When we have multiple objects f_1, f_2…… and f_i to fuse, image and encrypt via SPI, different encoded matrices B_1, B_2…… and B_i with resolutions of $N\times N$ are employed to sample the multiple objects. It is assumed that the jth illumination speckle C_j is generated by arranging the matrices achieved by multiplying multiplexed speckle S_j and B_1, B_2……B_i and can be expressed as:

$$\begin{aligned} &C_j(1:N,1:N) = B_1 \circ S_j, \\ &C_j(1:N,N+1:2N) = B_2 \circ S_j, \\ &\dots \\ &C_j(1:N,(i-1)N+1:iN) = B_i \circ S_j, \end{aligned} \tag{1}$$

Each sub-region with $N\times N$ pixels of illumination speckles corresponds to an object; thus, each illumination speckle can illuminate several objects simultaneously. The resolution of the restored image is equal to 128×128. The sub-regions of the above formula are arranged in columns for simplicity. In the actual system, the sub-regions can be arranged as required. In the system described here, four sub-regions are arranged in a 2×2 manner. The matrices of the illumination speckles are loaded into the DMD system via a computer. Multiple objects are placed in each division of the illumination speckle, and then, a series of illumination speckles are employed to illuminate multiple objects simultaneously.

The reflected intensities from the multiple objects can be expressed as

$$\begin{aligned} &g_{j,1} = \sum\nolimits_{N\times N} B_1 \circ S_j \circ f_1, \\ &g_{j,2} = \sum\nolimits_{N\times N} B_2 \circ S_j \circ f_2, \\ &\dots \\ &g_{j,i} = \sum\nolimits_{N\times N} B_i \circ S_j \circ f_i, \end{aligned} \tag{2}$$

The whole reflection intensity from several objects is detected by a single-pixel detector. Thus, the detected intensities of the single pixel detector can be written as

$$\sum_i g_{j,i} = \sum\nolimits_{N\times N} B_1 \circ S_j \circ f_1 + \sum\nolimits_{N\times N} B_2 \circ S_j \circ f_2 + \dots + \sum\nolimits_{N\times N} B_i \circ S_j \circ f_i, \tag{3}$$

Suppose binary encoded matrices have the following properties:

$$B_{i1} \circ B_{i2} = \begin{cases} 0 & i1 \neq i2 \\ B_{i1} & i1 = i2 \end{cases}, \tag{4}$$

$$\prod B_i = E, \tag{5}$$

where E represents a matrix with all entries are equal to 1, and $\prod$ indicates the accumulation of all matrices. In other words, multiple encoded matrices achieve complete sampling of the fused object information. In addition, they are orthogonal to each other. Further simplifying Eq. (3), we have

$$g_j = \sum\nolimits_{N\times N} S_j \circ \hat{f}, \tag{6}$$

where fused image $\hat{f} = B_1 \circ f_1 + B_2 \circ f_2 + ... + B_i \circ f_i$ represents the accumulation of the random samples from multiple objects, and $g_j = \sum_i g_{j,i}$. From Eq. (6), we can determine that the acquisition process can be described by the interaction between the multiplexed speckles and the fused image. Multiplexed speckles with Hadamard patterns are used in this paper. As the illumination speckles produced by the DMD system are binary, we create complementary pairs of illumination speckles H_+ and H_-. The intensities detected when illumination speckles H_{j+} and H_{j-} are used to illuminate the objects can be expressed as g_{j+} and g_{j-}, respectively, and then, the two intensities are subtracted. This process can be written as

$$g_j = g_{j+} - g_{j-} = \sum\nolimits_{N\times N} (H_{j+} \circ \hat{f} - H_{j-} \circ \hat{f}) = \sum\nolimits_{N\times N} (S_j \circ \hat{f}), \tag{7}$$

The iterative reconstruction method is employed to recover the fused object information, which can be expressed as

$$\hat{f} = \sum_j S_j \circ g_j, \tag{8}$$

where $\hat{f}$ is the recovered fusion image. Here, the number of the multiplexed speckles is equal to j. The above formula indicates that the fused image can be expressed as a weighted sum of multiplexed speckles based on the corresponding coefficients obtained from the detected intensities. The compression ratio is defined as the ratio of the number of multiplexed speckles to image pixels:

$$cr = j/N^2 \times 100\% . \tag{9}$$

During this analysis, a speckle cell is utilized as an image pixel.

Multi-object Demultiplexing

The above equation demonstrates that when the reflected intensities from multiple objects are detected, they are mixed together. Thus, the image of multiple objects is recovered by iterative reconstruction method. However, we must obtain the image of each individual object. Fortunately, based on the properties of encoded matrices, random samples of each object can be obtained as follows:

$$\hat{f}_i = B_i \circ \hat{f} = B_i \circ (B_1 \circ f_1 + B_2 \circ f_2 + ... + B_i \circ f_i) = B_i \circ f_i, \tag{10}$$

From the above formula, the Hadamard product of the fused image and encoded matrices can be used to obtain the corresponding random object information. Next, the complete information of each object can be determined with high precision by substituting the encoded matrices and the random sampled image in the CS algorithm. Optimizations can be achieved as follows:

$$f_i = ya_i \quad \text{subject to } \min \left\{ \left\| \hat{f}_i - B_i ya_i \right\|_2^2 + \lambda T(a_i) \right\}, \tag{11}$$

Here, y represents the transform to the chosen domain resulting in a sparse representation a_i, λ and T represent the regularization coefficient and function, respectively. The code employed for CS in this paper [17] is the function *Inpainting_GSR* of the software package. According to the above analysis, when the accurate encoded matrix cannot be obtained, accurate images of the objects cannot be recovered; that is, the encoded matrix can be utilized as a key to encrypt the object.

Image comparison based on correlation coefficients

To compare image acquisitions, we used the correlation coefficients between the under-sampled images and a reference image. This coefficient ranges from zero to one, depending on the resemblance of both images. Our reference image is always the image acquired without under-sampling (i.e., measuring at the Nyquist-Shannon criterion). The correlation coefficient is calculated with the following function:

$$r = \frac{\sum_m \sum_n (A_{mn} - \bar{A}) \circ (B_{mn} - \bar{B})}{\sqrt{\sum_m \sum_n (A_{mn} - \bar{A})^2 \circ \sum_m \sum_n (B_{mn} - \bar{B})^2}} , \tag{12}$$

where A and B are the image matrices with indices m and n, respectively, and $\bar{A}$ and $\bar{B}$ represent the mean values of the elements in A and B.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Nos. 11404344 and 41505019) and the CAS Innovation Fund Project (No. CXJJ-17S029).

Author Contributions

S. D.F. conceived, designed, supervised the study, interpreted the data, and wrote the manuscript. H. J. performed the experiments, analyzed the data and assisted in writing the manuscript. W. Y.J. conducted the experiments and analyzed the data. Y. K., X. C.B., L.D. and Z. W.Y. discussed the results and revised the manuscript.

Additional information

Competing financial interests: The authors declare no competing financial interests

References

1. Shapiro, J. H. & Boyd, R. W. The physics of ghost imaging. *Quantum Information Processing* **11**, 949-993, doi:10.1007/s11128-011-0356-5 (2012).
2. Sun, B. *et al.* 3D Computational Imaging with Single-Pixel Detectors. *Science* **340**, 844-847, doi:10.1126/science.1234454 (2013).
3. Duarte, M. F. *et al*. Single-pixel imaging via compressive sampling. IEEE Signal Process. Mag. **25**, 83–91 (2008).
4. Zhang, Z. B., Ma, X. & Zhong, J. G. Single-pixel imaging by means of Fourier spectrum acquisition. *Nature Communications* **6**, doi:Artn 622510.1038/Ncomms7225 (2015).
5. Morris, P. A., Aspden, R. S., Bell, J. E. C., Boyd, R. W. & Padgett, M. J. Imaging with a small number of photons. *Nature Communications* **6**, doi:Artn 591310.1038/Ncomms6913 (2015).
6. Ryczkowski, P., Barbier, M., Friberg, A. T., Dudley, J. M. & Genty, G. Ghost imaging in the time domain. *Nature Photonics* **10**, 167-+, doi:10.1038/Nphoton.2015.274 (2016).
7. M. J. Sun, M. P. Edgar, G. M. Gibson, B. Q. Sun, N. Radwell, R. Lamb, and M. J. Padgett, Single-pixel three-dimensional imaging with time-based depth resolution, Nat Commun **7**(2016).
8. Kong, L. J. *et al.* Encryption of ghost imaging. *Physical Review A* **88**, doi:Artn 01385210.1103/Physreva.88.013852 (2013).
9. Clemente, P., Duran, V., Torres-Company, V., Tajahuerce, E. & Lancis, J. Optical encryption based on computational ghost imaging. *Optics Letters* **35**, 2391-2393 (2010).
10. Chen, W. & Chen, X. D. Ghost imaging for three-dimensional optical security. *Applied Physics Letters* **103**, doi:Artn 22110610.1063/1.4836995 (2013).
11. Tanha, M., Kheradmand, R. & Ahmadi-Kandjani, S. Gray-scale and color optical encryption based on computational ghost imaging. Applied Physics Letters 101, doi:Artn 10110810.1063/1.4748875 (2012).
12. Candes, E. J. & Wakin, M. B. An introduction to compressive sampling. *IEEE Signal Processing Magazine* **25**, 21-30, doi:Doi 10.1109/Msp.2007.914731 (2008).
13. Hitomi, Y., Gu, J. W., Gupta, M., Mitsunaga, T. & Nayar, S. K. Video from a Single Coded Exposure Photograph using a Learned Over-Complete Dictionary. *2011 IEEE International Conference on Computer Vision (ICCV)*, 287-294 (2011).
14. Gao, L., Liang, J. Y., Li, C. Y. & Wang, L. H. V. Single-shot compressed ultrafast photography at one hundred billion frames per second. *Nature* **516**, 74-U159, doi:10.1038/nature14005 (2014).
15. Lin, X., Wetzstein, G., Liu, Y. B. & Dai, Q. H. Dual-coded compressive hyperspectral imaging. *Optics Letters* **39**, 2044-2047, doi:10.1364/Ol.39.002044 (2014).
16. O. Katz, E. Small, and Y. Silberberg, Looking around corners and through thin turbid layers in real time with scattered incoherent light, Nat Photonics **6**, 549-553 (2012).
17. J. Zhang, D. B. Zhao, and W. Gao, Group-Based Sparse Representation for Image Restoration, IEEE T Image Process **23**, 3336-3351 (2014).